Second Harmonic Magneto-Resistive Imaging to Authenticate and Recover Data from Magnetic Storage Media

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ABSTRACT

A scanning magneto-resistive microscope was developed that allows for high resolution imaging of magnetic tapes and digital media. By using second harmonic detection to remove thermal anomalies we are able to image sufficient lengths of tape for authentication purposes and for data recovery from damaged samples. This allows for high contrast images and direct conversion of the scanned information into originally recorded analog audio waveforms or digital data.

Keywords: Magneto-resistive imaging, data recovery, magnetic recording, forensics

1. INTRODUCTION

The imaging of magnetic patterns on tape media is important for forensic analysis and data recovery from damaged samples. These images are frequently used to authenticate evidence in criminal cases. The commonly used method of obtaining this information is to apply a fluid that has a suspension of small magnetic particles, i.e. "ferro-fluid" to the tape, allow the fluid to evaporate, and image the resulting patterns of particles with an optical microscope.[1–3] Two main problems with this magnetic imaging technique are that the sign of the magnetic field is not indicated (hence the signal cannot be converted directly into audio waveforms) and the technique can cause spurious errors on the digital media. In addition, when airline flight data tapes are heavily damaged there is currently no technique for recovering data from very fragile, short pieces (less than 10 cm) of tape.

Here we present a newly developed imaging technique, magneto-resistive (MR) microscopy that is based on technology developed for the data storage industry. The advantages of this technique are that it gives the sign of the magnetic field (hence analog waveforms can be recovered), it has a high dynamic range, the data are acquired and analyzed by a computer, and it is non-invasive. A wide range of samples have been studied including analog cassette tapes with read/write head stop events, VHS and S-VHS analog video tapes, digital audio tapes, 3.5 and 5 $\frac{1}{4}$ inch floppy disks, computer hard disks, and tape segments from airline flight data recorders. In this work, we describe the imaging technique, present representative images, and demonstrate that both analog audio waveforms and digital data can be recovered.

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2. APPARATUS

Magneto-resistive (MR) sensors have become a key element in the magnetic data storage industry over the past 30 years. MR sensors are comprised of a strip of magnetic material, usually a nickel-iron alloy, that changes resistance in an applied magnetic field. Two advantages of MR sensors are that the signal is independent of velocity (as opposed to an inductive sensor) and the strip can be scaled down to sub-μm dimensions. Research into the use of MR elements for streaming digital tape storage began in the mid-1970s,[4] and they were in mass production by the mid-1980s. This type of sensor was incorporated into magnetic hard disk drives in the early 1990s, and advances in this technology have been a major part of the increase in storage capacity of hard disk drives for computers seen over the past decade.

The sensors used in this work rely on the anisotropic MR (AMR) effect. The maximum resistance change of these sensors in saturation is on the order of 1% when a magnetic field is applied perpendicular to a current flow.[5] A constant DC bias current is applied to the sensor in most applications, allowing the resistance to be measured according to Ohm's law. This current also generates a magnetic field that is used to linearize the response of the sensor. One obstacle to the use of these elements is their inherent temperature sensitivity. As the devices are scaled down, the heat capacity is also reduced. Therefore, any dirt or irregularity on the storage media that comes into contact with the sensor can cause a jump in the resistance, i.e., a thermal asperity. It has been shown that thermal asperities can be rejected by using an alternating current (AC) bias. For AC bias at a relatively high frequency, f, the magnetic field from the sample modulates the amplitude of the sensor response at $2f$. This is due to the fact that the interaction of the bias current and magnetic moment of the sample is independent of the sign of the bias current.[6] This is referred to as second harmonic detection, and allows for low noise imaging of the magnetic fields above a magnetic storage tape, floppy disk, or hard disk.

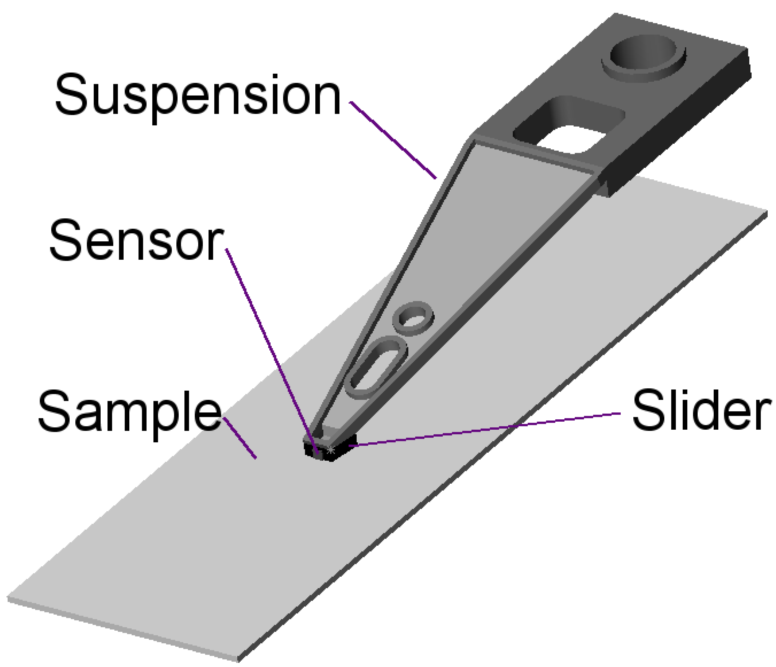

Figure 1. Drawing of head assembly (not to scale) from hard disk drive that is used in the imaging technique. Elements include suspension, slider, and magneto-resistive (MR) sensor element. The MR element is shown larger than actual size. MR elements used have a field sensitive gap of .05 μm and are 5 μm wide.

The method of data acquisition used with the MR microscope involves scanning an MR sensor over the sample many times to build an image. A drawing of the sensor is shown in Fig. 1. The suspension is a flexible strip that allows the highly polished slider to press on the sample with very low, constant force. The sensor is mounted on the front edge of the slider, and is in contact with the surface. The resolution along each scan is determined by the gap, and the lateral resolution (from scan to scan) is given by the width of the sensor. The assembly is mounted on a two-axis translation stage. This allows it to be scanned back and forth and side to side. The motion is controlled by a computer connected to servo-motor driven micrometers. The range of the translation can be up to 10 cm in either direction. The sensor position is monitored by the computer using quadrature encoders (0.6 μm resolution) mounted to the micrometer shafts.

The media sample is held in place using a micro-channel plate vacuum chuck mounted on a servo-motor controlled vertical translation stage.* This allows for manual loading of samples into the imaging apparatus. The sample is then raised to the slider to initiate the imaging process. Direct contact of the sample and head can be prevented by covering the sample with a thin sheet (1 to 10 μm) of polyester. We observe a 3 dB drop in signal using a 1 μm polyester sheet, with an additional 3 dB for every doubling of the thickness thereafter. The polyester is used primarily to prevent scraping or damage to delicate forensic evidence and it also ensures that vacuum is applied evenly to the sample by sealing any uncovered holes in the micro-channel plate.

The electronics for the system consists of an alternating current bias supply, a Wheatstone bridge, and a lock-in amplifier. The bridge is balanced so the first harmonic (1f = 10 kHz) signal from AC bias is nulled. The 2f signal at 20 kHz is then detected by the lock-in amplifier. The design point for the current bias of the AMR element is 12 mA and the resistance is typically 50 Ω. At 20 kHz we are above the majority of the 1/f noise for a metal film resistor.[7] Therefore, the measurement noise floor is determined by the electronic noise in the resistor and the Barkhausen noise of the magnetic sensor. The electronics noise is dominated by the shot and Johnson noise which, for these resistances, are 3×10^{-3} μV/$\sqrt{\text{Hz}}$ and 1×10^{-3} μV/$\sqrt{\text{Hz}}$, respectively. Added in quadrature, the intrinsic electronics noise level is less than 4×10^{-3} μV/$\sqrt{\text{Hz}}$. With a 10 ms time constant, the expected noise level is approximately 0.04 μV. From a cassette tape sample, a signal of about 50 μV is typically measured,† resulting in an electronics signal-to-noise ratio level (SNR) close to 62 dB. In addition, when the MR sensors are operated with an AC bias[6] the magnetic noise has been observed to reduce the SNR by 10 to 15 dB, giving an expected noise level of 45 to 50 dB. This matches closely to our observed experimental SNR levels.

The total time to acquire the image is determined by the resolution required and the time constant of the electronics. For authenticity analysis, samples every 25 μm along the length of the tape are sufficient. In order to recover an audio signal with bandwidth up to 4 kHz a sampling rate of 8 kHz is required. Since standard analog audio cassette tapes are recorded at 4.76 cm/s (1 $\frac{7}{8}$ inch/s), this sample rate translates to 6 μm sample spacing along the scan direction. Typical total scan times for an image of 1 s of cassette tape can take anywhere from 10 to 60 min, depending on the desired resolution and the number of scans across the width of the tape.

3. AUTHENTICATION OF EVIDENCE

In the forensics field, magnetic media are commonly used and are frequently admitted as evidence in court proceedings. Occasionally, this evidence is challenged and a determination is sought to discover if the tape is authentic, i.e. "has this tape been altered; is it original or a copy?" Although ferro-fluid continues to be an effective tool to determine the authenticity of analog audio cassette tapes, newer recording formats and modern recording systems require imaging techniques with improved SNR and higher contrast. In addition, recovery of analog waveform data directly from the scanned magnetic image greatly enhances the state of the art in forensic audio.

Analog audio cassette tape recorders must erase, record, and play. Some specialized decks use separate heads for each of these functions but most decks use a combined play/record head. Most machines leave distinctive recording features that can be revealed upon imaging the magnetic patterns left on the tape. More expensive, professional quality recorders are designed to minimize any magnetic artifacts of the recording process. In any case, if these features can be imaged then they can be used to determine the authenticity of the recording. When recording events occur, i.e. starts, stops, erasures and over-recordings, an examiner can determine whether the recording is original,

*The micro-channel plate is a glass plate with many holes (i.e. channels) having 10 μm diameter and 15 μm spacing. The microchannel plate technology was developed for electron amplification plates used in visible light image intensifiers. We have found that these plates make excellent vacuum chucks for magnetic tape media.

†This signal level is a fraction of what can be expected for an AMR element in a strong magnetic field because these inexpensive, commercial sensors are designed to detect very narrow transitions on a hard disk drive. We are currently experimenting with unshielded sensors and expect an order of magnitude larger signal. However, these sensors are not readily available commercially

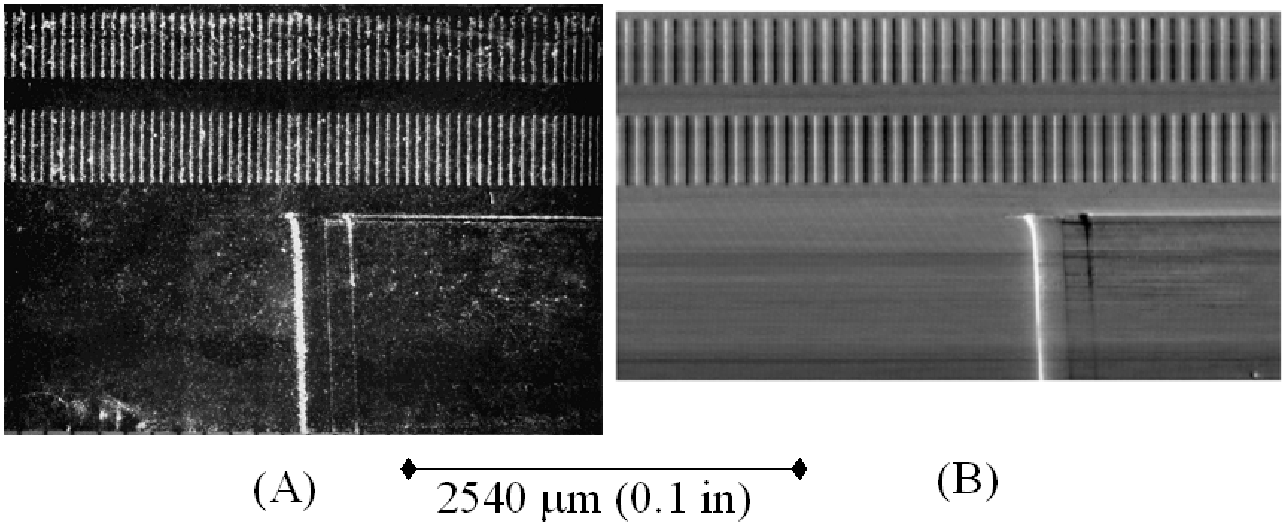

Figure 2. Analog audio cassette tape sample imaged using (A) conventional ferro-fluid technique and (B) Magneto-resistive microscope.

continuous, and unaltered. For example, Fig. 2(A) shows a ferro-fluid image of an audio cassette tape test sample. On the lower half of the image, one can see where a half-width (mono) erase head was stopped (going from left to right) after it erased the tape. Features to focus on are the edge line in the center of the tape that terminates at the stop event, as well as the number, spacing, and structure of the vertical lines that make up the stop event. Forensic audio experts are often able to relate these features to various parameters of the head that created them. A 400 Hz tone was also recorded using a pair of quarter-width heads (stereo) on the top half of the test sample, and are visible in Fig. 2(A) as a series of short vertical white lines.

For comparison, we show the same sample imaged with the MR microscope in Fig. 2(B) after the ferro-fluid without using the polyester protection layer. The image shows higher resolution of the same features noted above; however, there are also slightly darker streaks apparent that go the full length of the scan. These may be due to either the presence of intermittent contamination of the sensor or small offset shifts in the 2f signal from the magnetic modulation. We expect that either the use of polyester film to protect the head from contamination or normalization of the signal[6] will alleviate this problem. Important new features in Fig. 2(B) to note are the clarity of track edges, texture difference between the virgin vs. non-virgin areas (to the left and right of the erase head stop event, respectively) and the fact that the features left by the heads may be either darker or lighter than the background, whereas the corresponding features in Fig. 2(A) are always lighter. The first two points indicate that this technique may eventually be capable of determining with more certainty the type of recorder used and possibly even "fingerprinting" a specific machine. The last point demonstrates that the MR technique measures both the magnitude and direction of the magnetic field above the sample while the ferro-fluid indicates only the magnitude. In this particular demonstration, in fact, we discovered from the MR microscope image that the two quarter-width heads were recording signals 180 degrees out of phase with each other because the bright vs. dark lines (where the field is emanating from or going into the sample, respectively) of one channel match up with the opposite lines of the other channel. This is another signature of a recording that cannot be detected with ferro-fluid.

4. ANALOG WAVEFORM RECOVERY

As discussed in Sec. 3, a drawback of the ferro-fluid technique is that the particles accumulate at all magnetic transitions, regardless of the polarity of the transition. Therefore, the signal cannot be translated directly into an audio waveform without making assumptions about how the magnetic field changed. The MR microscope, however, maps both the direction and strength of the magnetic field. We show in Fig. 3 an image of 2.5 cm of audio cassette tape that has both a voice and test signal recorded. To demonstrate that the audio waveform can be obtained from

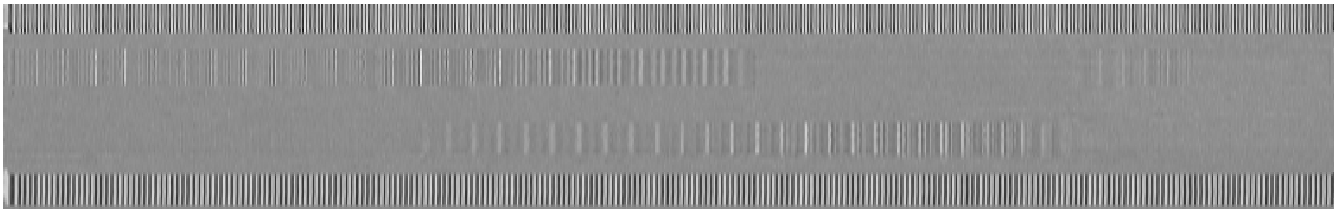

Figure 3. Image of analog audio cassette tape sample with “FBI” and 560 Hz test tone on the inner and outer tracks (side A, top, going from right to left). The word “NIST” and a 400 Hz test tone are recorded on the inner and outer tracks (side B, bottom, going left to right).

this image, in Fig. 4(A) we show a single, scan from the “F B I” track of Fig. 3. The bottom panel shows the audio wave that was sent to the recorder from the microphone. An expansion of the recorded and measured waveforms in the region of the letter “I” is shown in Fig. 4(B). The similarity of these two waveforms is evident in spite of the fact that no equalization has been applied to the signal from the tape recording. When the signal from the MR microscope is sent directly to an audio speaker, the voice of the person speaking can be clearly identified.

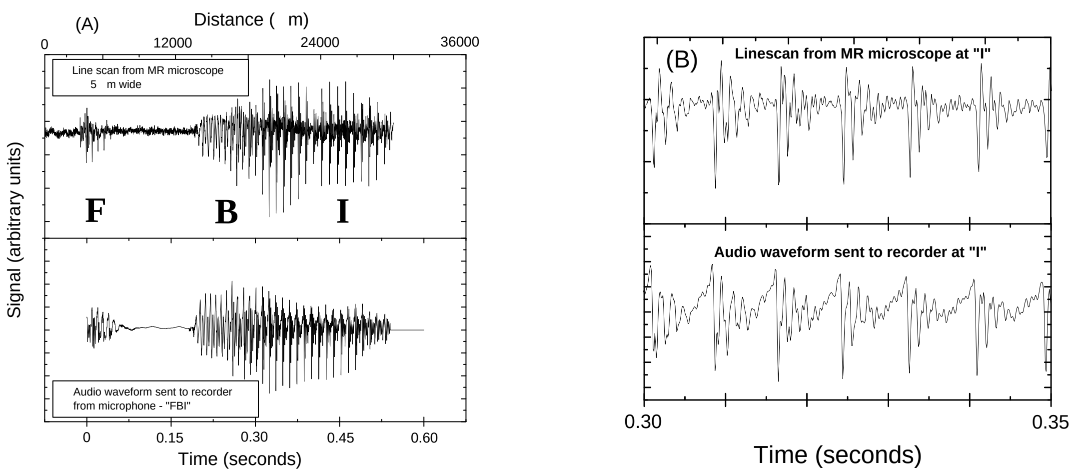

Figure 4. Panel(A) - Upper: A single linescan (5 μm wide) from Fig. 3 down the edge of the inner track of side A, Lower: Original audio waveform recorded on this track. Panel (B) - Expanded view of data from Panel (A) in the region of the letter “I”.

The main difference between the data from the top and bottom panels of Fig. 4(A) is the lower SNR in the MR microscope linescan ($\approx$25 dB). This noise is a combination of the media noise and the intrinsic noise in the MR element. The media noise is due to the fact that the line scan is a small fraction (0.8%) of the width of the track. When adjacent scans are averaged, we find that the linear voltage SNR increases as the square root of the number of scans, as expected for random noise. In decibels, the SNR increases as 10 $\log_{10}$(number of scans averaged). The maximum number of independent linescans across each track at this resolution is 120, hence the SNR will increase from about 25 dB to $25 + 10\log_{10}(120) = 46$ dB when these linescans are averaged. This is a typical SNR number for an analog audio cassette tape recording.

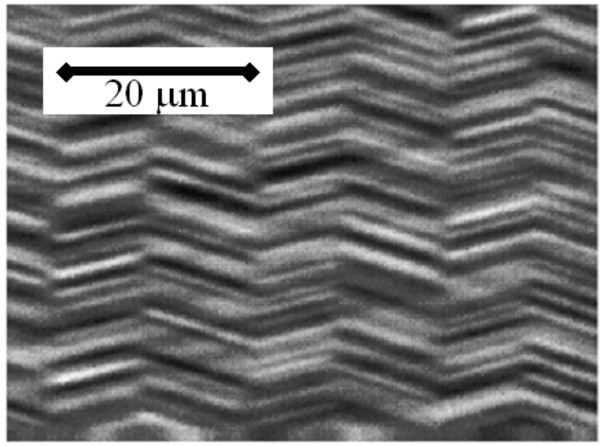

Figure 5. Image of digital audio tape (DAT) sample.

5. DIGITAL DATA RECOVERY

For digital media, this technique provides improved SNR, higher resolution, and no requirement for ferro-fluid, which has been found to contaminate most digital playback systems. Shown in Fig. 5 is an image of computer data recorded on a helical-scan digital audio tape (DAT). Because the features and artifacts are different for digital media, additional research is necessary to identify events indicative of alteration. However it is possible to read the low level binary data directly from these images. Uses of this would be to search for deleted (but not erased data) and the recovery of data from damaged samples. In particular, airline flight data recorders are occasionally destroyed in accidents, and it is desired to screen very small (2 to 10 cm long) bits of data tape that cannot be read with existing playback systems. The MR microscope works well for these samples.

Shown in Fig. 6 is a test sample of magnetic tape recorded with a typical eight-track flight data recorder. Seven of the horizontal tracks can be seen in the image, with a thin slice of the last track at the top. The data are written at 2246 bits/in (11 μm/bit) onto the tape in 768 bit blocks with inter-record gaps between them. These dimensions are well within the resolution and range of the MR microscope, and allow for the decoding of individual blocks of data.

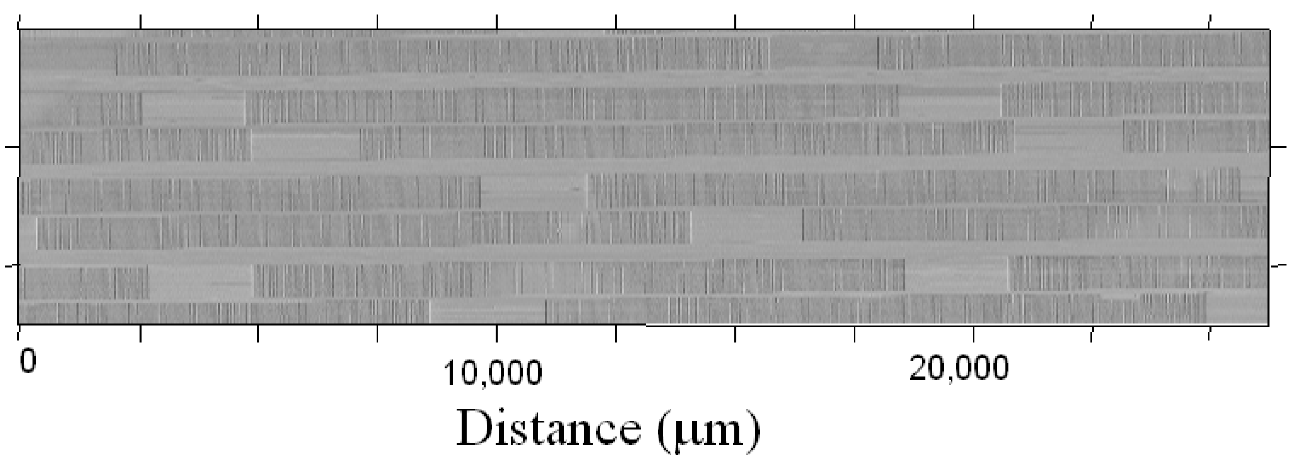

Figure 6. Image of sample from segment of 8-track flight data recorder. Complete blocks of data can be read, which may otherwise be not recoverable.

The data format is Harvard bi-phase coding, i.e. the recorded signal is clocked between hi/lo at 2246 bits/in, with the presence of an extra transition indicating a datum "1", otherwise it is a datum "0". We have written a program that converts each block of image data into binary data. Due to the large amount of data generated in this process and the random nature of the sample, we do not present a decoded block here. Rather, we show in Fig. 7 a magnified view of the region between 5000 and 5600 μm from Fig. 6. The relevant aspects of the data recovery process are evident in this figure. First, it can be seen that the data can be read directly from the image (see inset); however, the transitions between the white and black stripes are not sharp. This means that it is necessary to average several linescans to get a representative cross-section from a given track. In addition, the recording rate is only nominally constant, resulting in varying distances from bit-to-bit. This is demonstrated in the 3rd and 4th tracks from the bottom, where two strings of 0's appear side by side. Reading right to left in the direction of the arrow shown, the data tracks start out at the same phase (black to white) at point (a), and by the time they get to point (b) the signals are shifted by 90 degrees. This demonstrates the necessity for creating an algorithm that actively compensates for fluctuations in the tape velocity during recording.

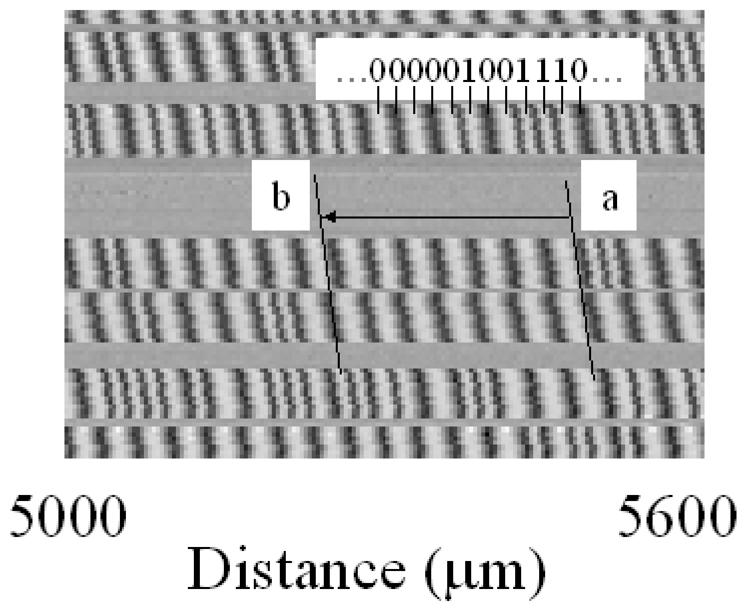

Figure 7. Magnified view from Fig. 6 showing that the recorded data can be read, either by inspection or automated computer program.

6. DISCUSSION

We have described and demonstrated the applicability of a magneto-resistive microscope as a non-invasive method for use in forensics analysis and data recovery. It compares favorably with the ferro-fluid technique that is widely used. Other techniques that have been recently developed include imaging using a magneto-optic (MO) garnet film placed in contact with the sample[8] and scanning SQUID microscopy.[9] The MO garnet film is complementary to the MR microscope because it allows for relatively quick optical inspection of the samples to identify regions of interest. However, data recovery may be complicated in the MO system by limited field of view and optical defects in the films. Advantages of the MR microscope over the scanning SQUID system are the lower cost, higher resolution, a self-aligned sensor, and no need for cryogens.

The most significant advantage of the MR microscope over all of these techniques is the intrinsic scalability of the sensor.[10] It has been demonstrated that large arrays of small sensors can be manufactured to read many tracks simultaneously. A system based on a multi-element sensor (200 - 400 elements) would be able to scan samples orders of magnitude faster than other techniques. This system, currently under development, will work similarly to a desk-top document scanner in principle, and allow for high resolution, real-time screening of magnetic media evidence. We expect a continuing need for improved imaging methods for magnetic analog and digital data tape recordings with an accompanying need for applications of high-technology sensors in this area.

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